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# A PALEOMAGNETIC STUDY OF TECTONICALLY DEFORMED RED BEDS OF THE LOWER GLARUS NAPPE COMPLEX, EASTERN SWITZERLAND

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Abstract. A paleomagnetic study at 15 sites (315 samples) in Permo-Triassic red beds of the Helvetic nappes of eastern Switzerland isolated stable characteristic and secondary remanent directions. Thermal demagnetization and isothermal remanent magnetization experiments suggest pigmentary hematite carries the characteristic direction. Secondary directions are scattered but may have been acquired during the Alpine deformation in the Oligocene and Miocene. The characteristic directions also show large between-site scatter. Anisotropy of magnetic susceptibility indicates that the hematite grains are flattened within the slaty cleavage, and that there is a north-south lineation. This anisotropy pattern implies that the magnetic grains were realigned by the Alpine deformation. It is not possible to explain the characteristic remanent magnetization deviations on a site-by-site basis, but the site mean directions are streaked along a great circle, the down dip direction of which is approximately parallel to the regional fold axes (60°/20°). This spread could be explained by a penetrative simple shear deformation associated with the nappe-internal deformation.



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## INTRODUCTION

A large part of geologic interest is now concentrated on deformed terrains, which have been traditionally avoided by paleomagnetists. However, as paleomagnetism has been shown to be a useful method in deciphering rotations and displacements of tectonically deformed areas, paleomagnetists have become more involved with studies of deformed rocks. Investigations of the effects of deformation on magnetization have been limited largely to theoretical and experimental observations [Blow and Hamilton, 1978; Kodama and Cox, 1978; Ozima, 1980].

Paleomagnetic studies of red beds in the Maritime Alps showed the effects of progressive deformation on remanent magnetization [Kligfield et al., 1983; Cogné and Perroud, 1985]. Kligfield et al. [1981] showed a relationship between the anisotropy of magnetic susceptibility (AMS) and the finite strain. Graham [1978] defined four major stages of progressive deformation in the Maritime Alps. The least deformed rocks show flattening of the finite strain and susceptibility anisotropy ellipsoids within the bedding plane due to compaction. The superposition of tectonic flattening on the compactional loading first leads to the formation of pencil structure. The strain and anisotropy ellipsoids are prolate with the elongated axis subparallel to the regional fold axes. As the tectonic deformation increases slaty cleavage develops, leading to oblate ellipsoids flattened in the cleavage plane. Further deformation causes the oblate strain and anisotropy ellipsoids to become extended down dip in the cleavage plane, giving a triaxial deformation ellipsoid.

The triaxial stage is not completely reached in the Maritime Alps, although hematite grains are realigned within the cleavage plane. The remanence directions are affected by distortional strains and deviate from the expected Permian directions [Kligfield et al., 1983; Lowrie et al., this issue].

Permian and Triassic red shales and slates from the Helvetic Nappes in eastern Switzerland provide an excellent example of rocks that have undergone triaxial stage deformation. There have been many studies analyzing the deformation, strain and metamorphic grade of these rocks [Oberholzer, 1933; Fisch, 1961; Schielly, 1964; Huber, 1964; Ryf, 1965; Kühn, 1966; Markus, 1967; Richter, 1968; Frey et al., 1974; Pfiffner, 1977, 1978, 1981; Milnes and Pfiffner, 1977, 1980; Siddans, 1979; Groshong et al., 1984]. The remanent magnetization of these red beds has been evaluated in order to observe the effects that these extreme strains have on the remanence.

## GEOLOGY

Red bed sediments of the Permian Verrucano and Triassic Quartenschiefer Formations are found in the Lower Glarus Nappe complex of the Helvetic zone. Four major stages of deformation, occurring from 40 Ma to 5 Ma before present, can be identified in the Helvetic zone of eastern Switzerland [Milnes and Pfiffner, 1977, 1980; Pfiffner, 1977, 1978, 1981]. These include: the Pizol phase, a period of tectonic burial with the emplacement of exotic flysch strips; the Cavistrau and Calanda phases, characterized by the formation of the fold and thrust structures and development of axial planar, thrust-parallel cleavage; and the Ruchi phase, with the formation of crenulation cleavage and with further displacement on the Glarus overthrust leading to an inversion of metamorphic zonation [Frey et al., 1974]. Only low grade metamorphism was reached during the time of main deformation in the study area [Frey et al., 1974; Siddans, 1979; Groshong et al., 1984].

Green reduction spots found in the shale-slate members of the Verrucano and Quartenschiefer formations show flattening in the cleavage plane. They also show a north-south extension in the gently south-dipping penetrative cleavage. The finite strain ellipsoids derived from these spots have been described by several authors [Ryf, 1965; Kühn, 1966; Siddans, 1979; Pfiffner, 1981]. Most of these analyses were limited to two-dimensions (Figure 1a). The intensity of deformation is heterogeneous, but an average intensity can be estimated from the spot measurements. Typical ratios of the strain principal axes ($X > Y > Z$) are between 1.65 and 3.53 (mean for sixteen sites, 2.36) for X/Y, and between 2.9 and 12.7 (mean 6.9) for X/Z. Fabric analysis on thin sections has been done by Siddans [1979], who showed that platelets of illites, chlorites and hematites are preferentially aligned in the slaty cleavage plane.

The fold axis orientation at the Malm level of stratigraphy in the Glarus area shows a consistent trend of N60°E. At the Triassic level the fold axes trend E-W along the Walensee and N-S in the extreme southeast, where sites 8 and 9 are located. The fold axes of the central area are scattered due to strain accommodation at fault terminations.

## SAMPLING AND MAGNETIC PROPERTIES

Fifteen sites (315 samples) were collected in the Lower Glarus Nappe complex, mainly from the Murgtal and Spitzmeilen areas (Figure 1b). Samples were taken in the field with a portable gasoline drill or as block samples which were later drilled out in the laboratory. Since the overall structure of the study area is one of an upright sequence, overturned sequences occur only locally (see Pfiffner, 1981, Figure 2, cross section 3). Overturned bedding can be excluded for all sites with the possible exception of site GV14.

The natural remanent magnetization (NRM) of the samples had intensities ranging from $1 \times 10^{-4}$ to $3 \times 10^{-2}$ A/m. Alternating field demagnetization, using a Schonstedt single-axis demagnetizer, indicated that there is practically no low coercivity component to the remanent magnetization. Over 80% of the NRM intensity remained after using peak fields of 100 mT.

Samples were thermally demagnetized progressively and vector analysis was used to isolate characteristic and secondary components of magnetization [Zijderveld,

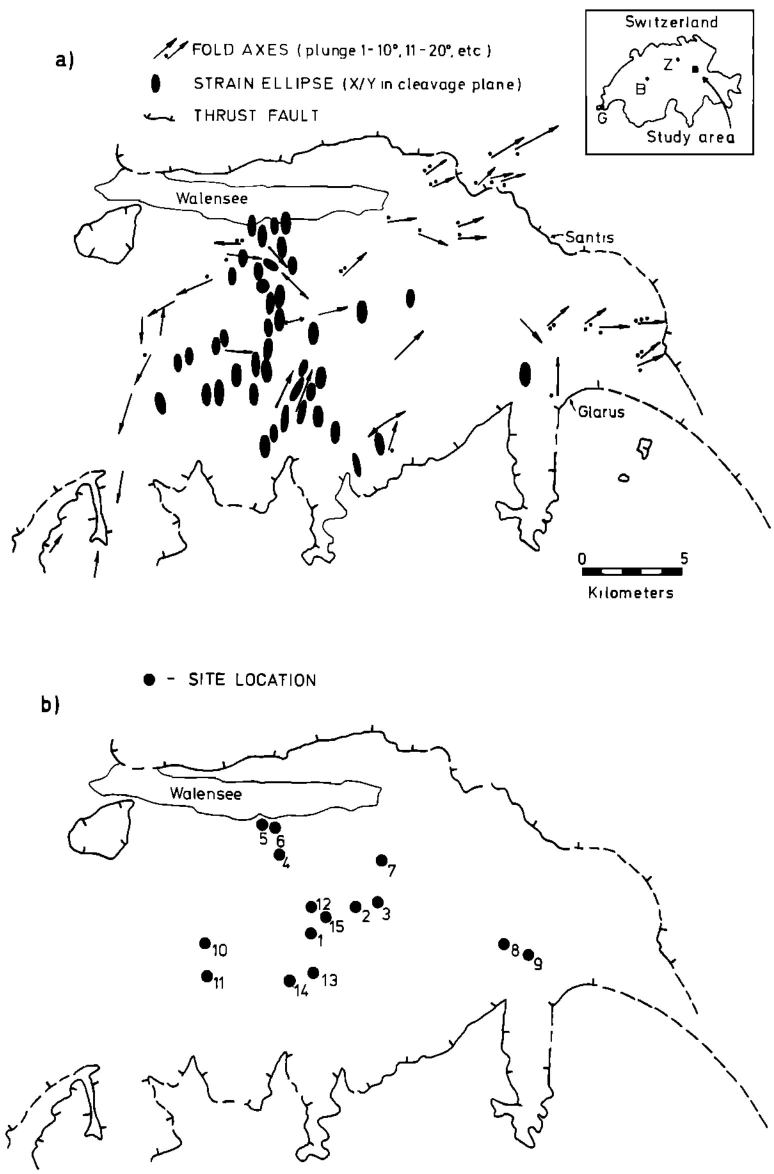


Fig. 1. Generalized map of the study area. (a) Structural data after Pfiffner [1981]; including results from Huber [1964], Schielly [1964], Ryf [1965], Kühn [1966], Markus [1967], Richter [1968] and Pfiffner [1981]. (b) Paleomagnetic site locations.

1967]. These components were defined from linear regression analysis where the linear fit was found to be statistically significant. Bulk susceptibility was measured on KLY-1 susceptibility bridge after each heating step to monitor changes in mineralogy during heating. Secondary components of magnetization were isolated, in general, between 300° and 600°C, and the characteristic remanent magnetization (ChRM) between 600° and 690°C (Figure 2). The anisotropy of magnetic susceptibility (AMS) was measured in unheated samples with a modified Digico anisotropy delineator [Schultz-Krutisch and Heller, 1985].

The acquisition curve of isothermal remanent magnetization (IRM) is concave upwards below 0.2T, suggesting the absence of a low coercivity component (Figure 3). The IRM then increases rapidly until 2.0T where the curve starts to flatten. Total saturation is not reached by 3.5T. Thermal

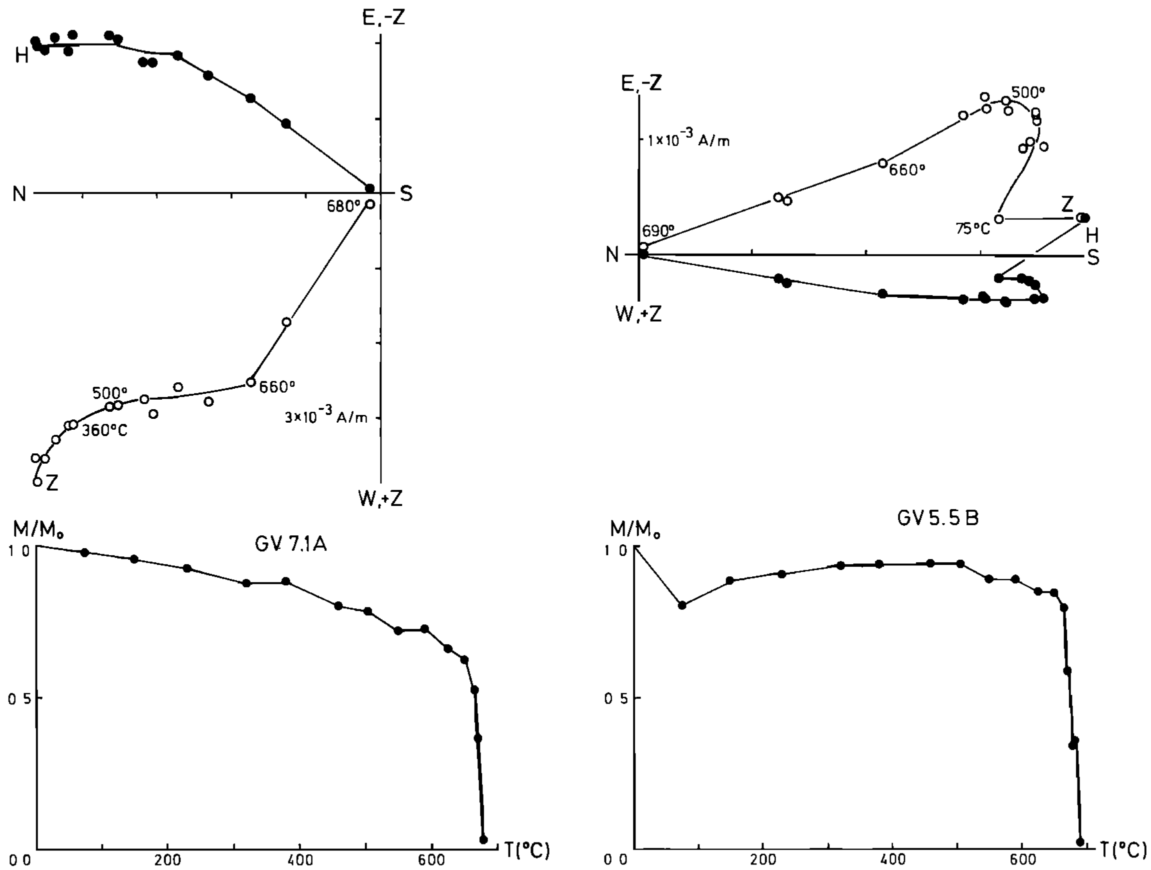


Fig. 2. Vector diagrams showing directional behavior and normalized plots showing intensity variation during thermal demagnetization. Closed symbols represent vector end points projected on the horizontal plane; open symbols are projections on the vertical N-S plane.

demagnetization of the saturation IRM shows over sixty percent of the saturation magnetization is still present by 600°C. The higher temperature, ChRM component is most probably carried by pigmentary hematite which has a narrow blocking temperature spectrum.

## RESULTS

### Analysis of Secondary Magnetization

Well-defined secondary directions ($\alpha_{95}$ <15°) could only be isolated at five of the fifteen sites; less well-defined secondary directions ($\alpha_{95}$ >20°) were found at another three sites; at the remaining seven sites the secondary directions could not be defined. Sites with negative inclinations were assumed to have a reversed polarity. Common polarity statistical analysis was carried out by converting all reverse directions to the lower hemisphere. One of the site directions lay more than two standard deviations from the mean and was excluded from further analysis. The mean direction before tectonic tilt correction for the remaining seven sites (D=14°, I=53°, k=18, $\alpha_{95}$=15°) is not statistically different from the present field direction of the study area, due to its large scatter (Figure 4). However, this mean direction is close to directions predicted for the Glarus region from the polar wander path for Europe [Irving, 1977] for ages less than 100 Ma. This may indicate that the secondary magnetization is related to the Tertiary deformation.

### Analysis of Characteristic Magnetization

The ChRM directions at thirteen of the fifteen sites are well-defined (within-site

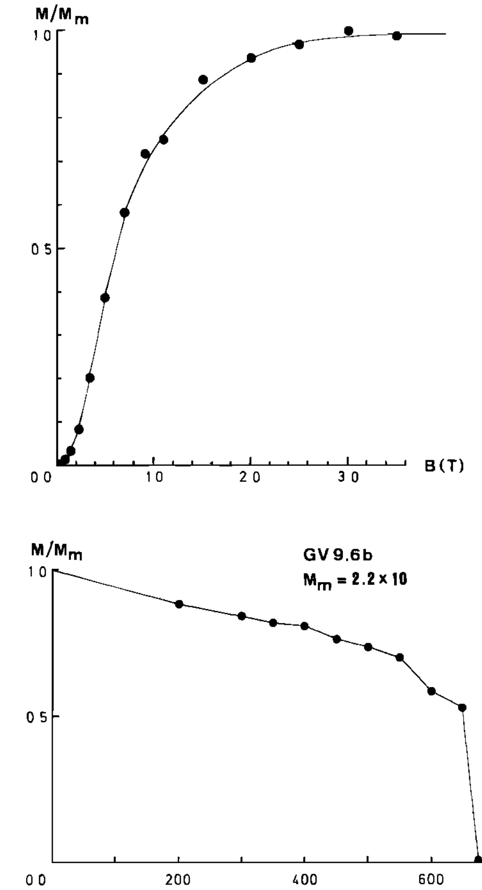


Fig. 3. Isothermal remanent magnetization (IRM) and thermal demagnetization of the saturation IRM for a representative specimen.

$\alpha_{95}$< 13°). Due to the intensity of deformation, bedding could not always be measured directly. The local bedding was used for the conventional tilt correction where measurable; otherwise the regional bedding was used, provided that the structure was simple. Within-site scatter is not changed by this correction. There is a large between-site scatter which is not altered appreciably by applying the regional tectonic tilt correction, because bedding was generally flat. The distribution of directions is both azimuthally uniform and Fisherian and gives a mean tilt-corrected direction for the thirteen sites of: D=73°, I=43° (k=4.7, $\alpha_{95}$=21°) (Figure 5).

## Magnetic Susceptibility Anisotropy

The rocks in the Glarus area have undergone extreme deformation as indicated by reduction spot strain markers. The AMS measured at each site showed a magnetic foliation and lineation similar to the deformation of the reduction spots (Figure 6). The minimum axes of susceptibility ($k_{min}$) are normal to the cleavage plane, and the maximum axes ($k_{max}$) are aligned in the cleavage plane. The AMS ellipsoid shapes range from oblate, for which $k_{max}$ and $k_{int}$ are girdled, to triaxial, where a lineation is also present.

The flattening of the AMS in the cleavage plane indicates that the hematite grains have had their basal planes aligned within the cleavage. This has also been reported by Siddans [1979] from thin section analysis. If the hematite grains have been reoriented, we can expect that the characteristic remanence vector also will have its orientation affected.

## DISCUSSION

An attempt to correct the remanence data for the deformation with the method of Hargraves [1959] was unsuccessful because of inherent limitations of the method [Lowrie et al., this issue].

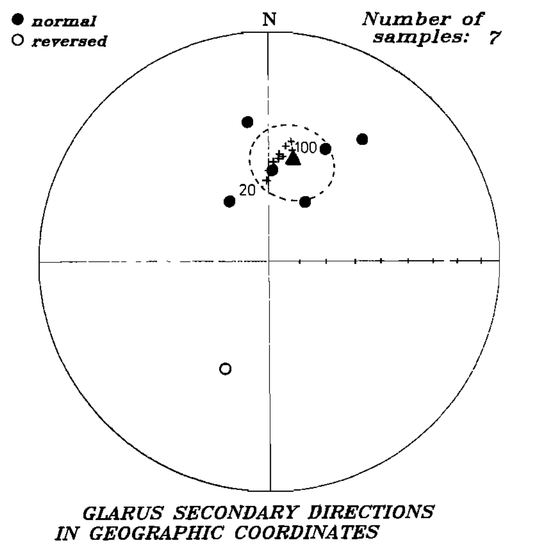


Fig. 4. Equal area plot showing the site means of secondary directions with their circle of confidence. Small crosses are directions calculated for the Glarus area from the APW for northeastern Eurasia, 100 m.y. to the present [Irving, 1977]. The triangle is the mean direction of the seven site means. Closed symbols are plotted on the lower hemisphere and open symbols on the upper hemisphere for this and subsequent figures.

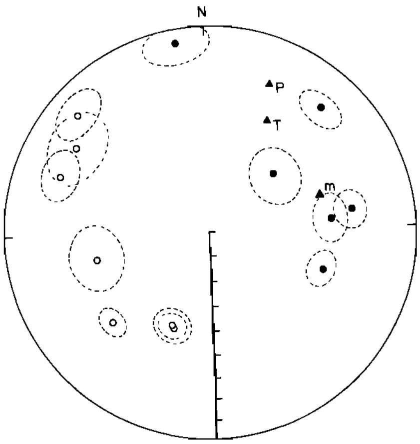


Fig. 5. ChRM directions are shown plotted with tectonic tilt correction. Triangle m is the mean ChRM direction, triangle P is the predicted Permian direction, and triangle T is the predicted Triassic direction for stable Europe [Van der Voo and French, 1974].

The Maritime Alps studies [Kligfield et al., 1983; Cogné and Perroud, 1985; Lowrie et al., this issue, Figure 4] showed that, as a result of increasing distortional strain in a rock, the scatter of the ChRM directions increases. The paleomagnetic vectors diverge from the expected direction to form a partial girdle about the trend of the regional fold axes. A similar feature is observed in the Glarus red beds of the present study (Figure 5). The spread of the directional data cannot be explained by dispersion on small circles corresponding to rigid body rotation about local or regional fold axes.

A simple model to approximate the overall internal deformation in the study area is one of heterogeneous, horizontal simple shear. Northward motion on the Glarus overthrust during the Calanda phase of deformation develops asymmetric folds with flattening within the gentle, south-dipping cleavage plane. Figure 7a illustrates the paleomagnetic vector (DB) in an undeformed state; for this study it is a typical Permo-Triassic direction (D=26°, I=31°). DC is the horizontal projection of DB. If the block is deformed by simple shear on a horizontal shear plane with motion from D to E, the point D will be displaced to D' while the point B stays fixed (Figure 7b). The remanence vector, if acting as a passive line element, has a new orientation defined by D'B. D'C is the new horizontal projection of D'B. Both the angles, $\alpha$ and $\phi$, will increase until $\alpha$=90°. The angle $\phi$ has now reached a maximum value, and starts to decrease with further shear ($\alpha$>90°).

Figure 7c illustrates that the same properties governing the behavior of $\alpha$ and $\phi$ during simple shear hold for a great circle. The declination, $\alpha$, increases with a northward horizontal simple shear, and the inclination, $\phi$, increases to a maximum value before decreasing. The great circle defines the path of increasing shear strain.

The model assumes a heterogeneous, horizontal simple shear and is only a crude approximation for the complexity of the deformation in the Lower Glarus Nappe complex. It also assumes that the hematite grains reorient in such a way that the remanence vectors rotate as passive line markers. The behavior of hematite platelets, the carrier of the remanence, in penetrative deformation is not yet understood.

The great circle distribution of measured ChRM directions does in fact appear to coincide with the great circle distribution caused by the simple shear model. However, the simple shear model predicts that ChRM directions should deviate furthest from the Permo-Triassic direction where the simple shear strain is

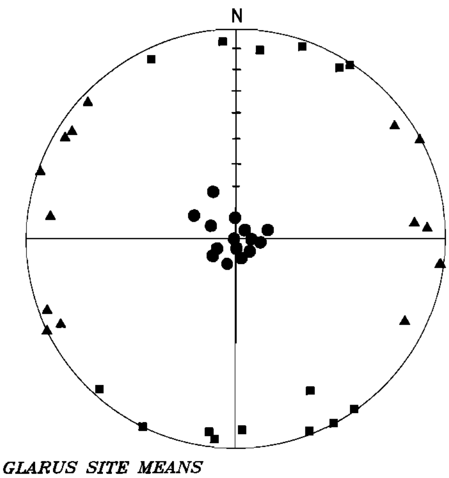


Fig. 6. Principal axes of the magnetic susceptibility ellipsoid for each site plotted with respect to the cleavage plane. Symbols: squares, $k_{max}$ axes; triangles, $k_{int}$ axes; and circles, $k_{min}$ axes.

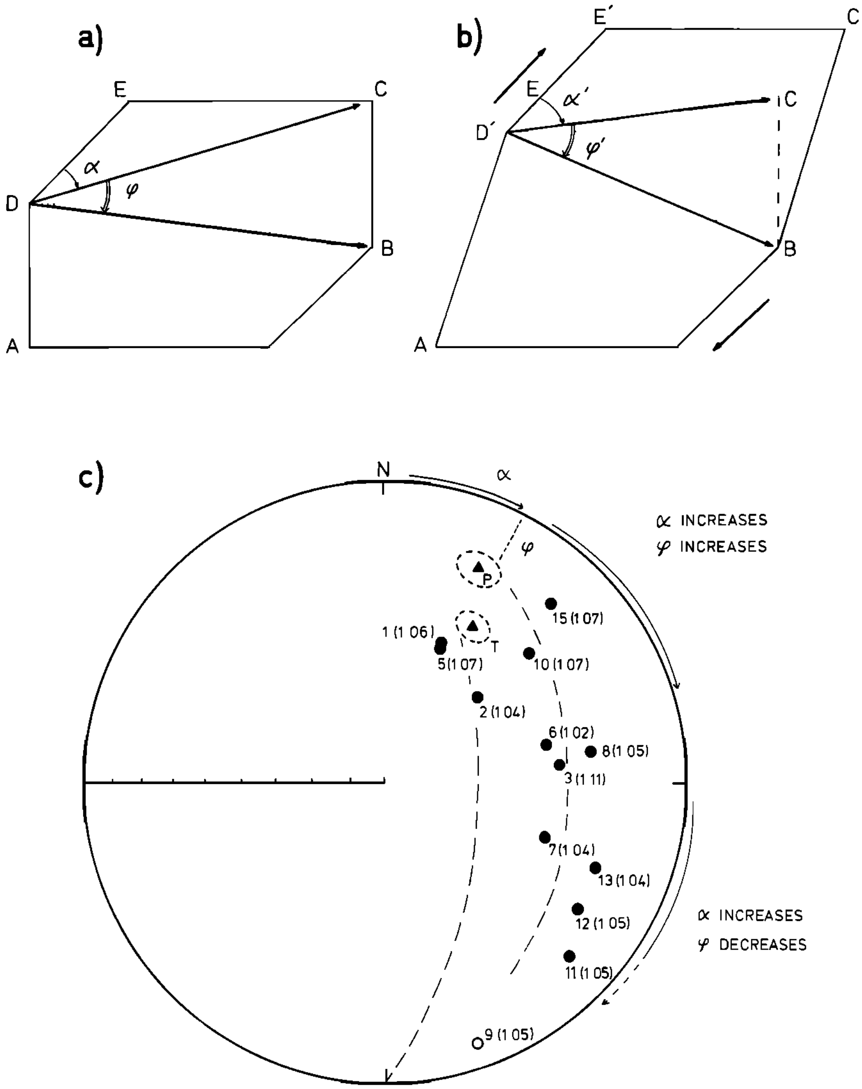


Fig. 7. Structural deformation model for horizontal simple shear. (a) Block before deformation; DB represents the remanence vector, α is the declination and ϕ is the inclination. (b) Block after undergoing simple shear; D'B represents the deformed remanence vector, α' is the declination after deformation and ϕ' is the inclination after deformation. (c) Equal area plot showing the dispersion of remanence vectors resulting from the deformation. The Permian and Triassic directions are as in Fig. 5 with computed circles of confidence. The two dashed great circles represent the envelope of expected dispersion of Permian and Triassic directions due to N-S simple shear. All directions are plotted on the lower hemisphere except for the very flat direction at site GV9. Numbers in parentheses give AMS axial ratios at numbered sites.

the highest. In fact, the axial ratios of the AMS ellipsoids projected on a N-S plane do not vary systematically in such a way along the great circle (Figure 7c).

Although the simple shear model is compatible with the observed directional distribution, and suggests that a systematic mechanism was responsible for the dispersion of the ChRM directions in these highly strained red beds, the AMS axial ratio data underline the preliminary nature of the model and indicate that it is not quantitatively adequate. It can be calculated for a three-dimensional simple shear model that an axial ratio for the strain ellipsoid of X:Z = 2.1 would be necessary to cause the Permo-Triassic direction to be displaced to the observed maximum $\phi$ (071/50). The predicted maximum $\phi$ for the model (090/54) would require a strain ellipsoid with an axial ratio of 2.7. These necessary strains are much lower than the average axial ratios (6.9) found in the Lower Glarus Nappe complex. However, this average value assumes that the reduction spots are initially spherical. The initial shape of the spots before the deformation is not known, and it may be oblate, i.e., X:Z greater than 1, due to original compaction. Since bedding and cleavage are both relatively flat, superposition of the strain ellipsoid over a bedding-flattened ellipsoid would result in a total ellipsoid which overestimates the shear strain. This interesting phenomenon must be better understood before paleomagnetic studies in highly deformed rocks can be meaningfully evaluated.

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